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EXECUTIVE SUMMARY

The technical term 'information' denotes the random aspect of variability within a data set, as evaluated by numerical computation. The information captured by a satellite radiometer depends on both the quality of the instrumentation, and on the variability of land use in the scene being viewed. Bigger and better satellite radiometers may be expected to acquire more and more information per unit area, but the incremental gain may not justify the increased cost and complexity of the more advanced system. Such a comparison cannot be carried out through examination of the engineering specifications; it requires analysis of the satellite data itself.

In this study the information contained in data from the visible and near-IR channels of the Landsat 4 TM and MSS is evaluated for five agricultural scenes, leading to the conclusion that the TM provides a significant advance in information gathering capability as expressed in terms of bits per pixel or bits per unit area. The six reflective channels of the TM acquire 18 bits of information per pixel out of a possible 6 x (8 bits) = 48 bits, while the four MSS channels acquire 10 bits of information per pixel out of a possible 4 x (7 bits) = 28 bits. Thus the TM and MSS are equally efficient in gathering information ($18/48 \approx 10/28$), contrary to the expected tendency toward lower efficiency as spatial resolution is improved and spectral channels are added to an observing system. The result is attributed to: 1) Superior selection of spectral channels in the TM; 2) Higher precision of the TM data, i.e., lower system noise; and 3) the advantage of higher spatial resolution, even in

agricultural areas where fields are larger than the MSS pixel size. Generally one would hope and expect that the improved information gathering capability of the TM would correspond closely to increased value and utility of the data to aid users in government and in the private sector.

Because the MSS lacks a thermal IR channel, the 10-12 micrometer data of the TM at 120 m resolution are analyzed theoretically using an energy balance approach. It appears that the TM thermal IR data are of interest mainly for mapping water bodies, which do not change temperature during the day, for assessing surface moistness, and for monitoring thermal features associated with human activity.

SECTION I. OVERVIEW OF THE INVESTIGATION.

A. Chronology

This contract, S-10772-C, began on November 17, 1983, following notification of acceptance of the investigator's proposal, negotiations, etc. Preliminary data sets such as 'lamp data', a 4 band TM scene of the Detroit, Michigan, area, etc., were already received prior to the initiation of the contract. Software development proceeded rapidly in conjunction with study of the northeast Arkansas scene, which was the first fully processed TM scene and also represented one of the test sites for this investigation. The decision was made early in the investigation to carry out image processing activities at the proposer's facility rather than on the Landsat asssessment system as originally proposed. The resulting delay, plus late acquisition of much of the required data (May, June, 1983) necessitated a 3 month contract extension, which was approved in November of 1983.

The assigned tasks were completed without difficulty in the period September through November of 1983, with prompt reporting stimulated through preparation of a paper for IEEE Transactions on Geoscience and Remote Sensing. This paper is included as 'Principal Findings' in the next section.

B. Facilities

Landsat Computer Compatible Tapes were sent by courier to the Washington Computer Center (WCC) for reformatting and statistical processing. FORTRAN programs were developed and executed at WCC on an IBM 3033. Small data sets (256x256 pixels) were reformatted and transmitted by phone to a microcomputer at the investigator's office in Beltsville. A desk top system was used for manipulation of these data sets.

The image display is built around an IEEE-696 microcomputer with FORTRAN compiler, floppy discs, and a 16 bit RGB color display, configured as 5 bit (32 levels) for each color, plus a graphics overlay plane. Figures 4 through 7 of Section II are photos from the system display.

C. Problems

Considering the experimental nature of the program and the complexity of satellite hardware, data processing, etc., the investigation ran quite smoothly. The major items of the Statement of Work (Appendix I) were completed, except that by agreement the classification work was deleted because of the lack of such a capability on the investigator's image processing system.

SECTION II. PRINCIPAL FINDINGS

The material in this section has been accepted for publication in IEEE Transactions on Geoscience and Remote Sensing. The figures cited in the text (1-11) are at the end of this section.

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ABSTRACT

Simultaneous data acquisition by the Landsat 4 Thematic Mapper (TM) and the Multispectral Scanner (MSS) permits the comparison of the two types of image data with respect to engineering performance and data applications. In this paper the 'information' contained in data from the visible and near-IR channels is evaluated for five agricultural scenes, leading to the conclusion that the TM provides a significant advance in information gathering capability as expressed in terms of bits per pixel or bits per unit area. The six reflective channels of the TM acquire 18 bits of information per pixel out of a possible 6 x (8 bits) = 48 bits, while the four MSS channels acquire 10 bits of information per pixel out of a possible 4 x (7 bits) = 28 bits. Thus the TM and MSS are equally efficient in gathering information ($18/48 \approx 10/28$), contrary to the expected tendency toward lower efficiency as spatial resolution is improved and spectral channels are added to an observing system. The result is attributed to: 1) Superior selection of spectral channels in the TM; 2) Higher precision of the TM data, i.e., lower system noise; and 3) the advantage of higher spatial resolution, even in agricultural areas where fields are larger than the MSS pixel size.

Because the MSS lacks a thermal IR channel, the 10-12 micrometer data of the TM at 120 m resolution are analyzed theoretically using an energy balance approach. It appears that the TM thermal IR data are of interest mainly for mapping water bodies, which do not change temperature during the day, for assessing surface moistness, and for monitoring thermal features associated with human activity.

I. INTRODUCTION

The last decade has seen a steady increase in the capability to monitor the earth's surface from satellite platforms. Systems now available or soon to be launched represent a range in data gathering ability from half hourly observations at 8 km spatial resolution by the geostationary satellites, to the 10 meter resolution at 26 day intervals from the SPOT satellite, which will be launched in 1985. These developments of instrumentation must now be considered in the context of the possible commercialization of space systems. Thus the satellite data user should select his data with many variables in mind, including cost. In this selection a primary consideration must be the scientific utility of the data, and its significance relative to alternative data sources. This study provides a statistical comparison of simultaneously acquired data from the Landsat 4 Thematic Mapper (TM) and the Multispectral Scanner (MSS) for 5 scenes acquired over agricultural areas.

Comparisons of different satellite data types have been infrequent in the past for two principal reasons: 1) the discrepancy of spatial resolution and the number and location of the spectral channels, etc., among previous satellites; and 2) the impossibility of obtaining data sets representing exactly the same location at exactly the same time from a common viewing perspective. The second reason is eliminated completely in the data sets acquired simultaneously from the Landsat 4 Thematic Mapper and Multispectral Scanner. Such scenes permit an unambiguous comparison of the information acquired at 30 m resolution in 6 spectral channels by TM with that acquired at 80 m resolution in 4 channels by the MSS.

It is not possible to provide a direct comparison of the two sensors for all applications of the data, as this will require specialized studies in each specific technical area. In this paper the data sets are compared for their information content, where the word 'entropy' is sometimes used in place of information, despite the fact that the historical meaning of entropy is rather different. Since the distinction is important in the consideration of satellite systems, the physicist's concept of entropy will be given. The original use and definition of the word entropy dates to the 1850's, when Clausius and Kelvin evaluated the mechanical work which could be extracted by a heat engine from a working fluid such as steam. This definition of entropy is

$$S = \int \frac{dq}{T} \qquad \text{(Joules/K)}$$

where dq is an increment of energy and T is temperature in degrees Kelvin. This definition pertains to a reversible process, with a more general thermodynamic formulation applying for irreversible processes. By the 1930's the quantum mechanics introduced new concepts which required a generalization of the definition of entropy. This generalization was developed within the framework of statistical mechanics (7), leading to the definition

$$S = - k \sum_i p_i \ln p_i \qquad \text{(Joules/K)} \qquad (1)$$

where $k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant, and the p_i are associated with the energy states of the physical system. For a brief yet complete description see Kittel (8).

In the context of satellite observations, entropy is concerned with the difference in energy between a '0' and a '1', where it is of great importance to ensure that electrical crosstalk, effects of cosmic rays, thermal fluctuations, etc., do not alter in a random way Landsat digital values once they are recorded at the detector of an observing instrument, during transmission to the ground, during computer processing, etc. Thus entropy pertains to the reliability and reproduceability of data transmission and processing, rather than to the numerical values of the data itself. With good design one does not see in processed data effects due to change of the value of entropy.

In this paper information is used in the sense of the classic papers on the subject as developed by Shannon (1). 'Information', corresponding to statistical variability, is defined as

$$H = -\sum_i p_i \log_2 p_i \qquad \text{(bits)} \qquad (2)$$

where p_i is the probability of a specific numerical value i in a series of measurements. This definition applies to both continuous and discrete (integer) data, but is commonly applied to digital data in the development of communications systems. Note the difference of the logarithms in equations 1 and 2, and the fact that the physicist's entropy is associated with energy. Figure 1 illustrates the histogram of a data set which is characterized as 8 bit data and the histogram of data carrying 1 bit of information. The 0-255 abscissa on both graphs represents the potential of the data to carry 8 bits of information. The 1 bit data could, in principal, be stored in a computer or on tape or transmitted from point to point at 1 bit per data value, after the coding DN84 = 0, DN226 = 1. Such data compression techniques reduce the bandwidth needed to transfer data from one location to another, and/or they reduce the volume of data as stored on magnetic tape, etc. Figure 2 illustrates the histogram of data carrying 2.75 bits of information per measurement. Procedures such as that due to Huffman (2) may be used to compress data as implied by the computation of information content.

The definition of information in equation 2 may be generalized when multiple data channels are considered, as in the case of multispectral image data. Information corresponds to interchannel variability. For example, if measured values in two spectral channels are known to be equal, the second carries no information and may be eliminated from the data set.

Such redundancy is dealt with in this paper through the principal components transformation (3), in which a linear transformation of variables yields a more efficient and compact representation of the original data set. A further reduction in information content is implied if temporal or spatial correlation exists in the data stream, e.g., from sample to sample along an image line. Figure 3 demonstrates this correlation in an idealized fashion; the graph approximates a portion of a scan line in the Imperial Valley of California, where field sizes are quite large (figure 4). Figure 3 also illustrates the coding procedure called run-length encoding, in which the data value is followed by its repetition factor. The principles described above have been summarized and applied to some image data sets, including Landsat, by Gonzalez and Wintz (4) and others (5,6), to which we refer the reader. The information content of the reflective channels of Landsat 4 is considered in Section II.

The Thematic Mapper carries an additional channel in the thermal infrared (10.4-12.5) micrometers. This channel has no counterpart in the MSS. These data are acquired at 120 m resolution, instead of the 30 m of the other 6 TM channels. In addition this spectral interval responds to different physical influences, and may produce misleading conclusions if lumped together with the 6 reflected channels, as has been illustrated with thermal IR data from

Landsat 3 (9). For this reason the significance of the thermal IR data is evaluated by theoretical analysis, and by comparison with data from an earlier research satellite, the Heat Capacity Mapping Mission (10), which produced data at 481 m spatial resolution. The thermal infrared data are considered in Section 3. In the concluding section an important parameter, namely frequency of observation, is discussed as it affects the value of satellite observations. The TM is an outstanding high resolution sensor, but the 16 day repeat cycle of observations limits utility for some applications.

II. COMPARISON OF THE INFORMATION CONTENT OF TM AND MSS REFLECTIVE DATA

The analysis is based on 5 matching scenes acquired by Landsat 4 during its early months of operation. Table 1 lists the locations, dates and scene numbers for the respective image pairs. These scenes, which represent a reasonable geographic sample of agricultural areas in the United States, are from the late growing season in the U.S. The planned selection of scenes from mid growing season, i.e., June and July, was not available because of the launch date of the satellite (July 16, 1982), and the degradation of the power system which prevented paired scene acquisitions during the middle of 1983. It now appears that this was favorable for the objectives of this study, as the variability represented in the scenes in table 1 is greater than would occur in mid-summer, when agricultural areas become a sea of green vegetation.

As with many geophysical data the variability and hence the information content of the Landsat data is dependent on both the geography of the specific region, and on the size of the area in question. If the size of the region is held constant, one expects to find greater information per unit area in a heterogeneous area, such as a city, or a finely divided agricultural area within China or India, than in a uniform region such as a desert or a grassy plain. Thus for the comparison of MSS and TM it is important to select matching areas.

On the other hand it is evident that information content (bits/area) will increase as larger and larger areas are considered. Thus if one begins with a modest size agricultural area and steadily expands the size of the area evaluated, this area will ultimately include mountains, deserts, forested equatorial regions, oceans, polar ice, etc. This increasing geographical diversity will produce a corresponding growth of the variance of the data, and a resulting increase of information content. Thus as a practical matter one must select a fixed area, whether large or small, in comparing the capabilities of the Landsat 4 TM and MSS. The computed values of H apply strictly only to the size areas which were used in the computation.

In the present analysis matching areas were selected representing 256 x 256 pixels for the MSS, and 512 x 512 pixels for the Thematic Mapper. Since the MSS data are acquired at 80 m spatial resolution, but processed to 57 m, the resulting data are not completely equivalent at a 2:1 ratio to the 28.5 m resolution of the processed TM data. Comparison of the TM with the MSS 'A' data (calibrated, but not resampled), instead of the 'P' data (calibrated and resampled during geometric rectification) could be done in principle, but other differences between TM and MSS such as precision (8 bit versus 6 bit digitation), etc., also complicate the whole issue. In this paper each subarea corresponds to a square 14.6 km on a side, or 21,300 hectares.

For historical reasons the NASA nomenclature for the order of the TM spectral bands is out of sequence. Thus in the NASA ordering the sequence

(1,2,..6,7) corresponds to wavelength values described roughly as 0.4, 0.5, 0.6, 0.8, 1.5, 11., and 2.2 micrometers, i.e., bands 6 and 7 are out of order. In this paper we shall refer to the bands in logical order (L), so that NASA bands 6 and 7 become L7 and L6, respectively. In this section band L7, the thermal infrared band, is omitted from the analysis because it represents a different physical regime.

Table 2 presents the comparison of the information content representing the average of three subareas from each of the 5 scenes. The values are for the calibrated data as provided on user tapes. Some variation from area to area is noticeable within the three subareas of each scene, as would be expected.

These values compare with a possible 8 bits per channel from the TM and 7 bits per channel from the MSS. The MSS data are transmitted as 6 bit data, then 'decompressed', meaning that the range of values 0-63 is mapped through a non-linear lookup table to the range 0-127. Examination of histograms of the MSS data shows that detector to detector variations produce calibration differences which cause shifts in the lookup tables. The result is to fill in most holes in the histograms which would be expected from the simple 1-1 mapping, so the data appear to have 7 bit precision.

The fact that all values of H are less than the theoretical limit is expected because the saturation radiances for both systems are set well above levels for typical ground reflectances, even for high solar incidence angles. The scenes discussed here are from summer and fall seasons, but from latitudes some 20-40 degrees north of maximum insolation. Data values for MSS and TM fall generally in the lower half of the possible range, representing a corresponding decrease from theoretically attainable information values.

Bright clouds would greatly increase the values of H. Of course such data are not useful for land applications, and the few clouds present in these scenes were avoided during selection of subareas.

If all other factors were equal one would expect the TM data to carry roughly 1 bit per spectral channel more than the MSS data, since the TM data are sampled to 8 bit precision, and the MSS data after decompression represent 7 bit data. Simple arithmetic shows that this relationship is approximately valid.

A single feature stands out in the results expressed in table 1: TM bands 5 and L6 are superior to the shorter wavelength bands 1, 2 and 3, in that they have a higher information content. This is a key factor in the conclusion to be developed; the TM represents a substantial improvement over the MSS. At the next level of analysis it is appropriate to compute the redundancy among spectral channels on a pixel by pixel basis. This has been carried out through a principal components analysis of the data for each of the 15 subareas. The procedure forms linear combinations of the measurements (x_1, x_2,., x_6) such that the rotated axes are aligned with the statistically independent components of variability in the data. The resulting values of information content are presented in table 3, with the conventional ordering such that the first of the transformed vectors corresponds to the greatest variability, the second to the second greatest, etc. The transformation matrices are not required for the present discussion. It must be emphasized that the new variables are not related in 1-1 fashion with the old x's, so that table 3 cannot be compared term by term with table 2. Obviously spectral redundancy exists in the data from both instruments. Comparing the mean of the sums from tables 2 and 3 it appears that about 5 bits of 29 represent redundancy in the TM data, while about 3 bits in 17 are redundant in the MSS data. One would generally expect increased redundancy as more and more spectral channels are added. Examination of correlations among the TM channels shows that channels 5 and L6 are statistically relatively independent of channels 1-4 (Table 4). This fact largely accounts for the high information content of the TM data, even after the principal components transformation.

As a next step spatial redundancy of the data is considered. This effect may be estimated by use of the difference operator which replaces each value except the first of a sequence by its difference from the preceding value. Thus $x_i' = x_i - x_{i-1}$ where i indicates the pixel number along a line. This replacement is called a delta transformation (4). The information content of the differenced data is given in table 5. In some cases the differenced data for components 5 and 6 of TM and 3 and 4 of MSS have a larger information content than the principal components data as given in table 3. In this case the lower of the two values has been given. This effect occurs because differentiating a noisy signal increases the variability of the signal. Subtraction of the mean of the sums from tables 3 and 5 shows that approximately 3.5 bits of 24 represent spatial redundancy in the TM data, while approximately 1.7 bits of 14 represent redundancy in the MSS data. The amount of this redundancy is related to field size. The subarea represented in figure 4 shows the effect most strongly: the delta transformed TM data carry 5.2 bits less information than the principal components data, i.e., 22.8 to 17.6 bits per pixel. The fact that the TM data are not more highly correlated in space is a little surprising, since most agricultural fields are considerably larger than the .09 hectare pixel size to the TM.

It should be noted that both the principal components transformation and the delta transformation possess inverses, so that the original sensor data may be recovered from the transformed data, if desired. However, this is not true if fractional values are rounded off to integer values during the principal component transformation.

A last factor must be considered in the estimation of the information content of data from the two instruments. This factor is noise, whether due to instrumentation and data processing, or to random variability in the reflectivity of the earth's surface. Even if this variability in the image data is due to true reflectivity variations at the earth's surface it carries no information if it is spatially disordered so that it has no interpretation. In such a case auxiliary ground truth data would be required to understand this spatial variability. In the present instance this effect is considered by subjective examination of the image data. Figure 5 illustrates one of the test areas in the Iowa scene, as displayed with 5 bits of precision (32 gray levels). In figure 6 the same areas are displayed with 3 bits precision, where the high bits have been used in the display. Such a display corresponds to rounding off the data by throwing away the lower order bits. It leads to a cartoon-like display, as occurs when classification is used to partition a region into a small number of gray levels corresponding to various types of land use. In figure 7 the same area is shown using the low 3 bits from the data. As the higher bits are discarded the image becomes more and more noisy, corresponding to random very small variations in the satellite observed reflectivity. This display method has been used to evaluate the number of the spectral components which appear physically meaningful in the TM and MSS data. The resulting conclusions are subjective, but plausible. The fourth principal component of the MSS data is unuseable, representing periodic noise which exists at low levels in the MSS data. This effect has been identified with noise in the spacecraft power supply. Similarly the sixth principal component of the TM data lacks structure, except for infrequent 5-20 pixel banding in locations near field boundaries. This effect is believed to be due to the line replacement algorithm which replaces data from failed detectors by that from an adjacent line. All other data appears to be 'real' in at least one of the five scenes, i.e., to have spatial coherence which could, at least in principal, be identified with true surface variability. After deleting TM row 6 and MSS row 4 from table 5 one concludes that the TM acquires about 18 bits of information per pixel, the MSS about 10.

The final result of the comparison is expressed by computing the efficiency of the two instruments, as given by the ratio (bits of information)/(possible bits of information)x100, where the possible values are 4 x (7 bits) for MSS, 6 x (8 bits) for TM. For the MSS this efficiency factor is (10/28)x100 = 36%, while for the TM the value is (18/48)x100 = 38%. Data from both instruments could be compressed by a factor greater than 2. The ratios are essentially equal, so the efficiency of information collection is equivalent for the two instruments.

The conclusion is more favorable to the TM than expected. Generally the MSS has adequate spatial resolution to resolve most fields in representative agricultural areas. One would expect the TM to provide only a limited increase in information per pixel or per unit area because of the small number of mixed pixels which occur at field boundaries as a fraction of the total area of a scene. Evidently the effect is substantial.

Similarly because of interchannel correlations one would expect the additional spectral channels of the TM to augment only slightly the information contained in the MSS channels. The strong variability of the new channels 5 and L6, and their independence from channels 1-4, explains the substantial information gain in the 6 channels of the TM. Finally the higher precision of the TM at 8 bits per channel is justified by scrutiny of the low order bits of the data as transformed to principal components. The increase in the potential utility of TM data compared to MSS is proportional to the improvement in engineering specifications.

III. EVALUATION OF THERMAL INFRARED DATA

Band L7 of the Thematic Mapper acquires data in the thermal infrared (10.5-12.5) micrometers, at 120 m spatial resolution. This wavelength range represents principally radiation emitted from the earth's surface or from clouds in the field of view, rather than reflected solar radiation. Due to the $T^{4.2}$ dependence of radiation at this wavelength (11) the data relate directly to the earth's surface temperature as modified slightly by atmospheric effects (12). The behavior of surface temperature is not described by a single physical parameter, as it results from a balance of the energy fluxes of radiation, sensible heat transfer to the atmosphere, the latent heat flux of evaporation and the exchange of heat with the ground. The most straightforward technique for analyzing thermal IR data is to model the temperature behavior of the earth's surface as a function of meteorological factors such as air temperature, relative humidity, windspeed, etc., and as a function of characteristics of the surface itself. It has been shown previously (13,14,15) that two parameters are responsible for most variability of surface temperature: the first is surface moistness, here called moisture availability, which affects the rate of surface evaporation and hence influences the 24 hour mean of surface temperature; and second is diurnal heat capacity, representing the heat storing capacity of a near surface layer of the ground, which largely determines the amplitude of the day-night temperature variation. Physically, the moisture availability influences the latent heat flux LE through the equation

$$LE = \frac{\rho_a L(mq_s - q_a)}{r}$$

where m is moisture availability, q_s is specific humidity of the surface at saturation, q_a specific humidity of the air, L is the energy of vaporization of water, ρ_a is the density of air, and r is a resistance factor. Thus m = q(surface)/q(saturation), corresponding to relative humidity. Diurnal heat capacity D is given by

$$D = (\omega\rho c\lambda)^{1/2} \qquad (W/m^2C)$$

where $\omega = (2\pi/1 \text{ day})$ is the angular frequency of insolation, ρc is volumetric heat capacity (J/m^3C), and λ is thermal conductivity (W/mC). Evidently accurate determination of these two variables requires measurement of temperature at least twice during the day. Figure 8 illustrates computed values of surface temperature, T_s, at 13:30 local time and at 2:30 local time, corresponding to the observation times of the Heat Capacity Mapping Mission (HCMM), a satellite with the observation times optimized for estimating surface characteristics and energy balance. By locating the intersection of the appropriate day and night temperature curves in the figure, one determines the corresponding values of moisture availability and diurnal heat capacity which produced the observed temperatures. These curves were produced from meteorological data from Spokane, Washington, in July 1978, corresponding to data acquisition by the HCMM.

Figure 9 illustrates the equivalent temperature values at the times corresponding to Landsat overpasses. Several important differences exist. The HCMM acquired data in a 720 km wide swath, so that 12 hour coverage was acquired over most of the United States at frequent intervals - typically each 5 days. In contrast the narrow Landsat swath produces 12 hour coverage only for a set of small narrow diamonds oriented north-south and centered at 40°N. Thus a typical location one acquires only one pass on a given day and the day-night temperature pair in figure 9 is not determined, but only the locus of points on the corresponding day or night curve, depending on which observations were acquired on that particular day. Therefore interpretation of day and night passes must be considered separately.

From figure 9 it is clear that Landsat day passes do indeed provide reasonable estimation of moisture availability for the wetter (upper) end of the scale. For example, an observed temperature of 30°C implies a range of 0.7 to 0.9 in moisture availability. By comparing with figure 10 it appears that the Landsat day observations are not greatly inferior to those of the HCMM day observations, being less definitive principally at low values of moisture availability (higher surface temperatures). Unfortunately the 16 day repeat cycle of the Landsat observations is rather low for monitoring a rapidly changing variable such as surface moisture.

Returning to figure 9 with reference to night passes it is apparent that the Landsat data provide little information because of the substantial ambiguity associated with lack of knowledge of the corresponding day temperature.

Here the later observations of the HCMM yield a clear advantage (compare with figure 8), as the night temperatures are oriented more vertically at low values of surface moisture. Such dry conditions correspond to prevailing conditions in many geologic areas. It also suggests why night thermal IR observations are desired by geologists for exploration purposes, as diurnal heat capacity is to some extent indicative of the rocks and minerals present at the earth's surface. Figures 10 and 11 illustrate that even at 480 meter spatial resolution the HCMM night observations are competitive with the L7 channel of the TM. Thus timing of observations during the daily cycle is quite important for understanding thermal infrared data.

Because the TM thermal IR data have no unambiguous theoretical interpretation they appear to be best suited for mapping of temperature variations of water bodies, especially in the neighborhood of power plants, because these water temperatures are scarcely affected by the diurnal cycle, and for inference of localized temperature anomolies, as may be found in industrialized areas.

IV. CONCLUSION

In sections II and III the information content of the TM and MSS have been compared, the reflective channels, TM 1-L6, and MSS 1-4, by direct computation, the L7 channel of TM by consideration of analytic procedures for evaluating thermal IR data. The hypothesis that the TM is significantly better than the MSS in a statistical sense may be considered as verified. To demonstrate that the TM's increased information, in the technical sense as used here, leads to a corresponding increase in practical or cognitive information, is a task that must be addressed by each discipline and by each user of the data. Simple examination of photographic products and manipulation and display of image data suggests that the utility of the TM data will indeed be far greater than that of the MSS.

Unfortunately, the comparison cannot end at this point for the user community. Satellite data are acquired on a continuing basis, and the user must consider the cost of a data set, and the frequency of observations as they pertain to his application. While the capabilities of the TM are outstanding, the 16 day repeat cycle of observations is rather long. Considerations of data cost and coverage frequency suggest that two or more multispectral scanners are a plausible alternative for assessment of agricultural conditions on a regional or national scale. For some applications the 9 day repeat cycle once available previously from two Landsats may be a minimum requirement (16,17). Further study and comparison of TM and MSS is clearly desirable.

The approach used here should facilitate evaluation of future remote sensing systems, since the difficult tradeoffs between user needs and instrumental design can be addressed at a more quantitative level. Engineering design should minimize redundancy and maximize information content versus system cost. Data users may evaluate the utility of each bit of information versus their applications requirements.

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FIGURES

Figure 1. Left - Histogram of 8 bit data; all values (DN) occur with equal probability in the range 0-255. Right - Histogram of 1 bit data; only 2 of the 256 possible values are represented.

Figure 2. Histogram of data carrying 2.75 bits/value.

Figure 3. Data values along a hypothetical image line having substantial sample to sample redundancy. Each value is followed by its repeat factor.

Figure 4. Large agricultural fields in the Imperial Valley illustrate spatial redundancy. The graph in figure 3 represents a slightly idealized version of the line indicated at the top of this TM image.

Figure 5. This TM subimage from the Iowa scene is displayed as 32 gray levels (5 bits). This is the first principal component.

Figure 6. The area in figure 5 is portrayed using 8 gray levels corresponding to the high 3 bits of the data.

Figure 7. The area in figure 5 is portrayed using 8 gray levels corresponding to the low 3 bits of the data. Note that patterns are visible in the data.

Figure 8. Computed day and night surface temperature values are plotted as functions of moisture availability and diurnal heat capacity for the 2:30 LT, 13:30 LT overpass times of the Heat Capacity Mapping Mission. Day temperature curves are approximately horizontal, night temperature curves are nearly vertical at low values of moisture availability.

Figure 9. Surface temperature values similar to Figure 8, except for the 10:00 LT, 21:00 LT overpass times of Landsat 4 at northern mid-latitudes. Day temperature curves slope from upper left toward lower right.

Figure 10. Landsat L7 image acquired at night over east central New York State, scene center N 43-10, W 74-35, image number 40096-02072. Black smudges toward the right are cold clouds. The image has good spatial detail but lacks contrast. Enhancement or enlargement brings out striping associated with multiple detectors.

Figure 11. Night thermal IR image from the HCMM for the same area as figure 9. Image identification A0078-07250. Striping was produced during film generation. Temperature contrast increases during the night, and features appear which are not recognizable in the Landsat data, such as the hill/plain discontinuity indicated by arrows.

Table 1. Scenes used for comparison of Landsat 4 Thematic Mapper and Multispectral Scanner.

Location	Scene identification	Acquisition date
N.E. Arkansas	40037 - 16031	22 August 1982
N.W. Iowa	40072 - 16325	26 September 1982
W. Kentucky	40094 - 15574	18 October 1982
Washington, D.C.	40109 - 15140	2 November 1982
Imperial Valley, CA	40149 - 17444	12 December 1982

Table 2. Information (bits/pixel) of multispectral data.

	Arkansas	Iowa	Kentucky	D. C.	California
			Thematic Mapper		
Band					
1	4.38	3.71	4.90	4.33	4.28
2	4.03	3.13	4.37	3.81	3.70
3	4.56	4.23	5.12	4.42	4.64
4	6.55	5.30	5.66	5.25	5.15
5	5.68	5.29	6.39	5.83	5.36
L6	5.05	4.71	5.80	4.98	4.71
SUM	30.25	26.37	32.62	28.62	27.84
			Multispectral Scanner		
1	3.51	2.82	4.06	3.50	3.33
2	4.03	3.66	4.71	3.92	4.12
3	5.18	4.52	5.03	4.67	4.57
4	4.47	4.47	4.78	4.33	4.45
SUM	17.19	15.47	18.58	16.42	16.47

Table 3. Information following principal components transformation.

	Arkansas	Iowa	Kentucky	D. C.	California
			Thematic Mapper		
Component					
1	6.59	5.71	6.80	6.17	5.73
2	6.03	5.16	5.64	5.12	5.09
3	4.37	3.82	4.44	4.25	4.17
4	3.37	3.11	3.44	3.10	2.93
5	2.73	2.96	2.81	2.77	2.52
6	2.27	1.96	2.05	2.00	1.97
SUM	25.36	22.72	25.18	23.41	22.41
			Multispectral Scanner		
1	5.64	4.67	5.51	5.12	4.91
2	4.24	3.71	4.86	3.84	4.16
3	2.48	2.47	2.65	2.65	2.63
4	2.23	2.03	2.38	2.34	2.38
SUM	14.59	12.28	15.40	13.95	14.08

Table 4. A TM correlation matrix illustrating the fact that bands 5 and L6 are relatively uncorrelated with bands 1-4.

Band	1	2	3	4	5	L6
1	1.000	.915	.884	.122	.537	.749
2		1.000	.896	.261	.620	.786
3			1.000	-.038	.556	.850
4				1.000	.433	.045
5					1.000	.782
6						1.000

Table 5. Information following delta (difference) transformation.

Delta component	Arkansas	Iowa	Kentucky	D. C.	California
			Thematic Mapper		
1	5.23	4.22	5.21	4.88	4.02
2	4.79	3.89	4.53	4.09	3.62
3	3.79	3.19	3.97	3.71	3.38
4	3.22	2.82	3.25	3.03	2.86
5	2.72	2.81	2.79	2.74	2.52
6	2.22	1.96	2.05	2.00	1.96
SUM	21.97	18.89	21.80	20.45	18.36
			Multispectral Scanner		
1	4.45	3.80	4.53	4.21	3.73
2	3.62	3.13	3.87	3.31	3.31
3	2.48	2.47	2.65	2.66	2.63
4	2.23	2.03	2.38	2.34	2.38
SUM	12.78	11.43	13.43	12.52	12.05

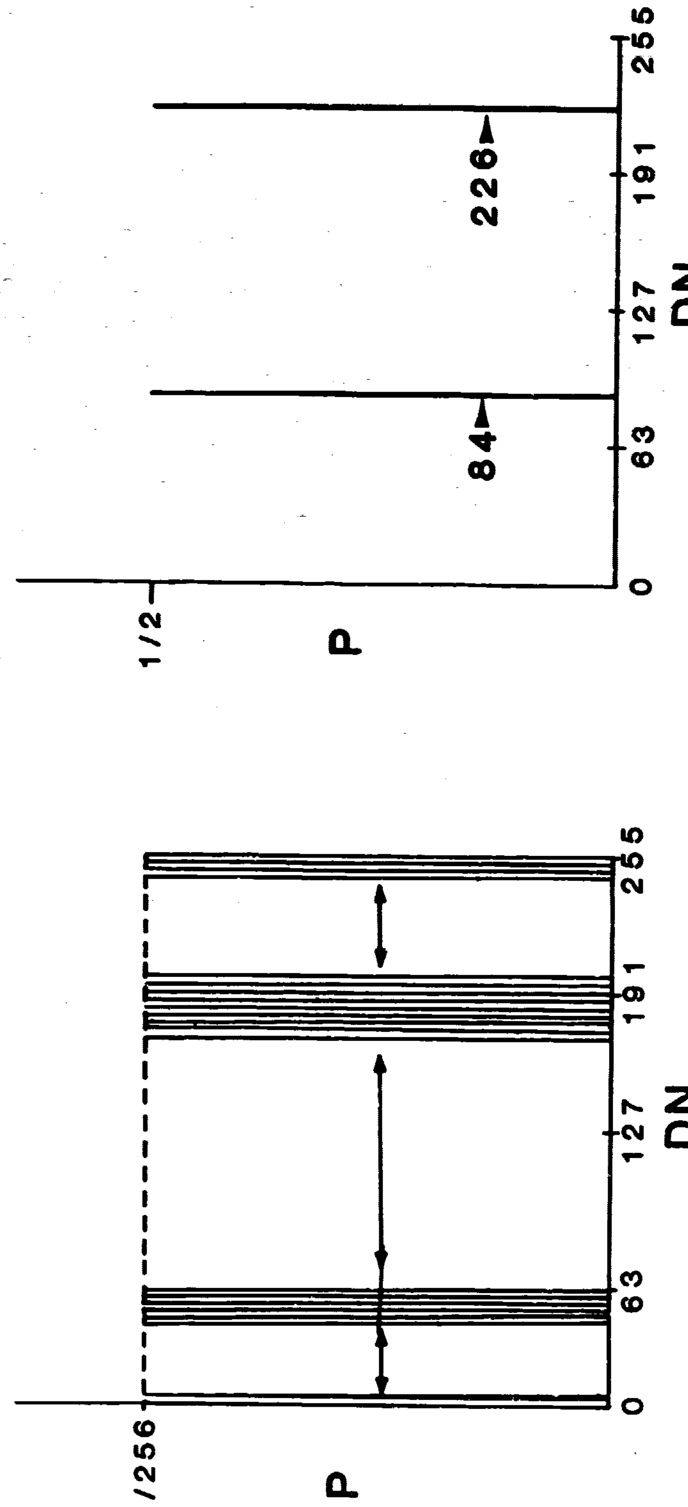

Figure 1

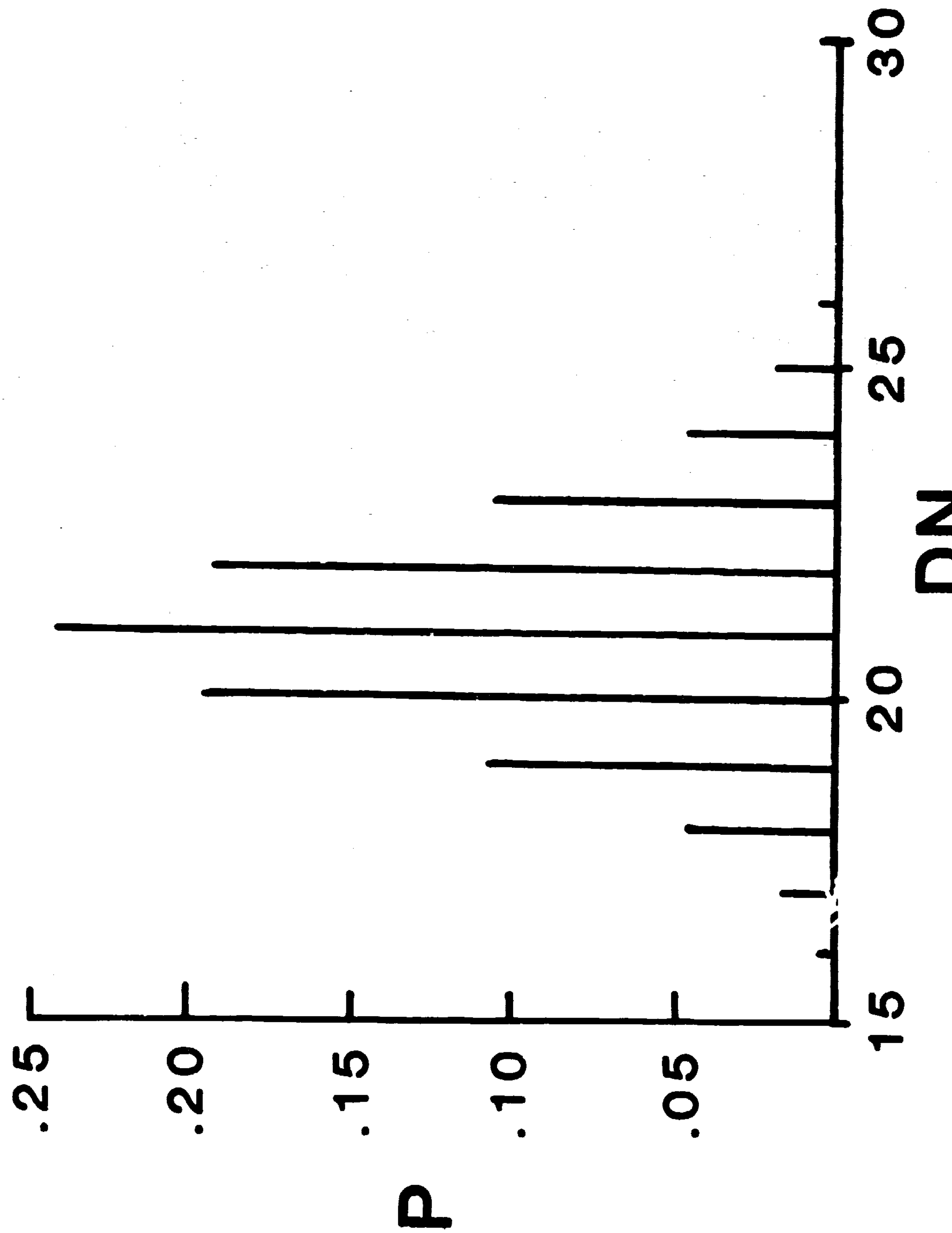

Figure 2

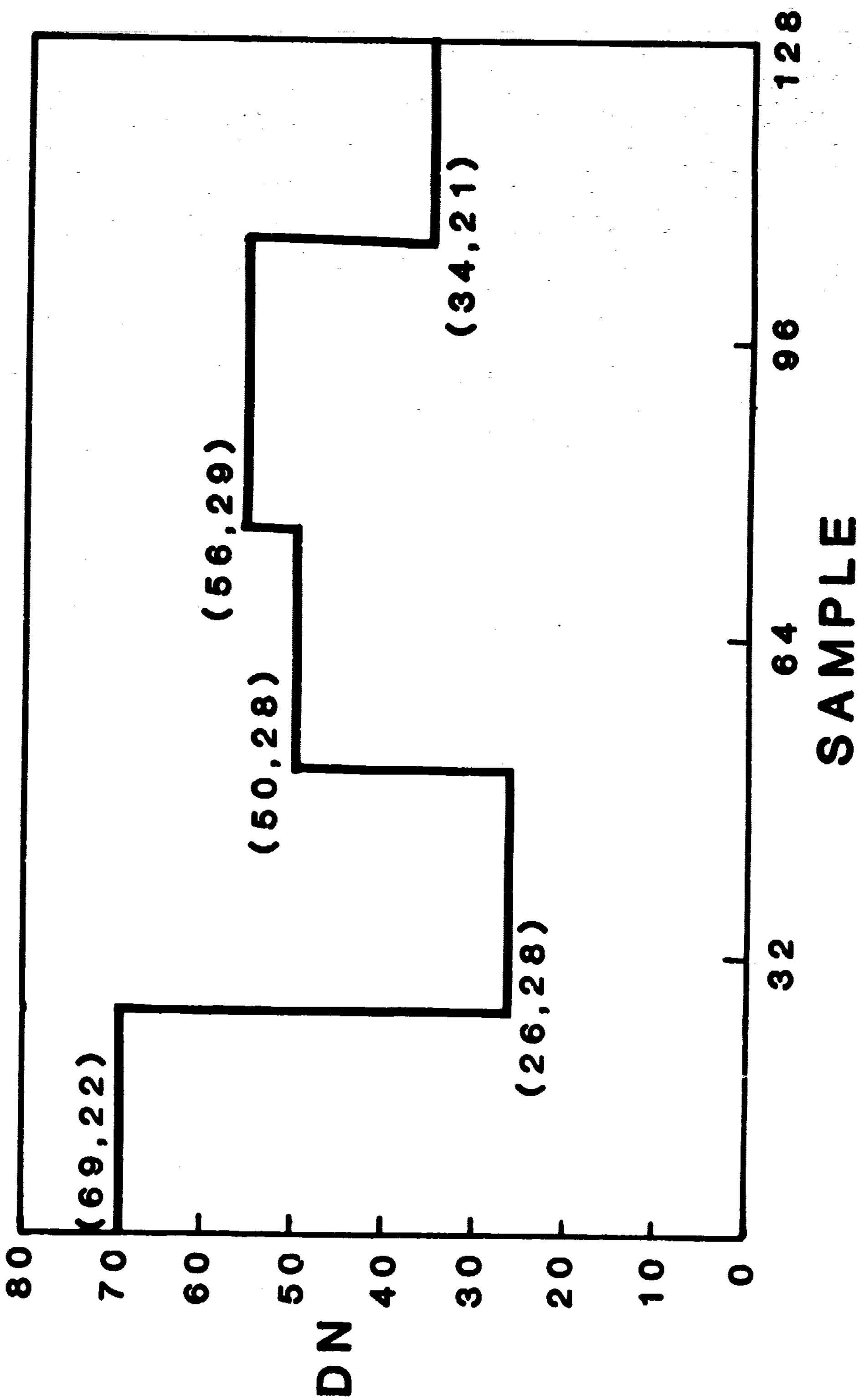

Figure 3

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OF POOR QUALITY

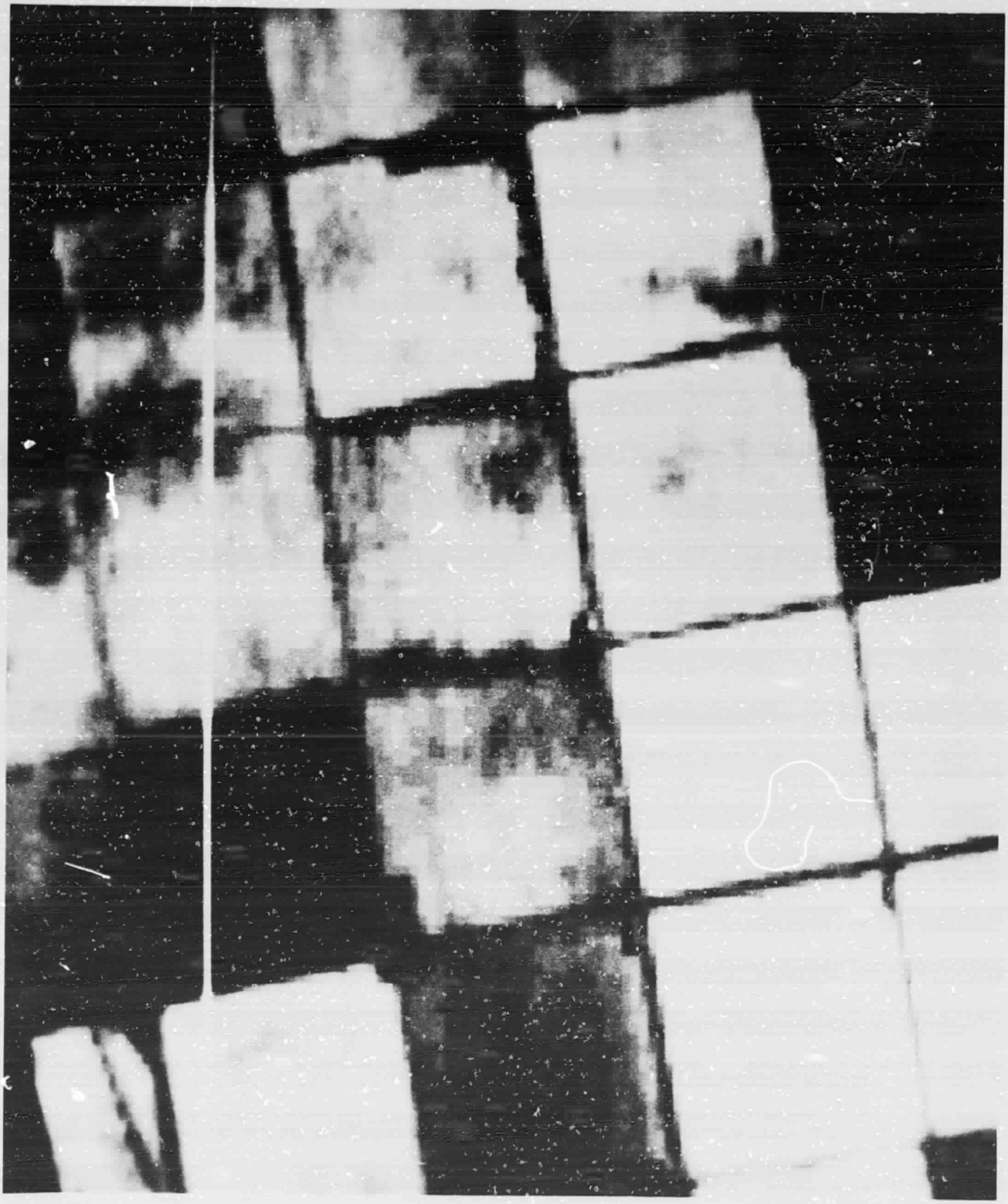

Figure 4

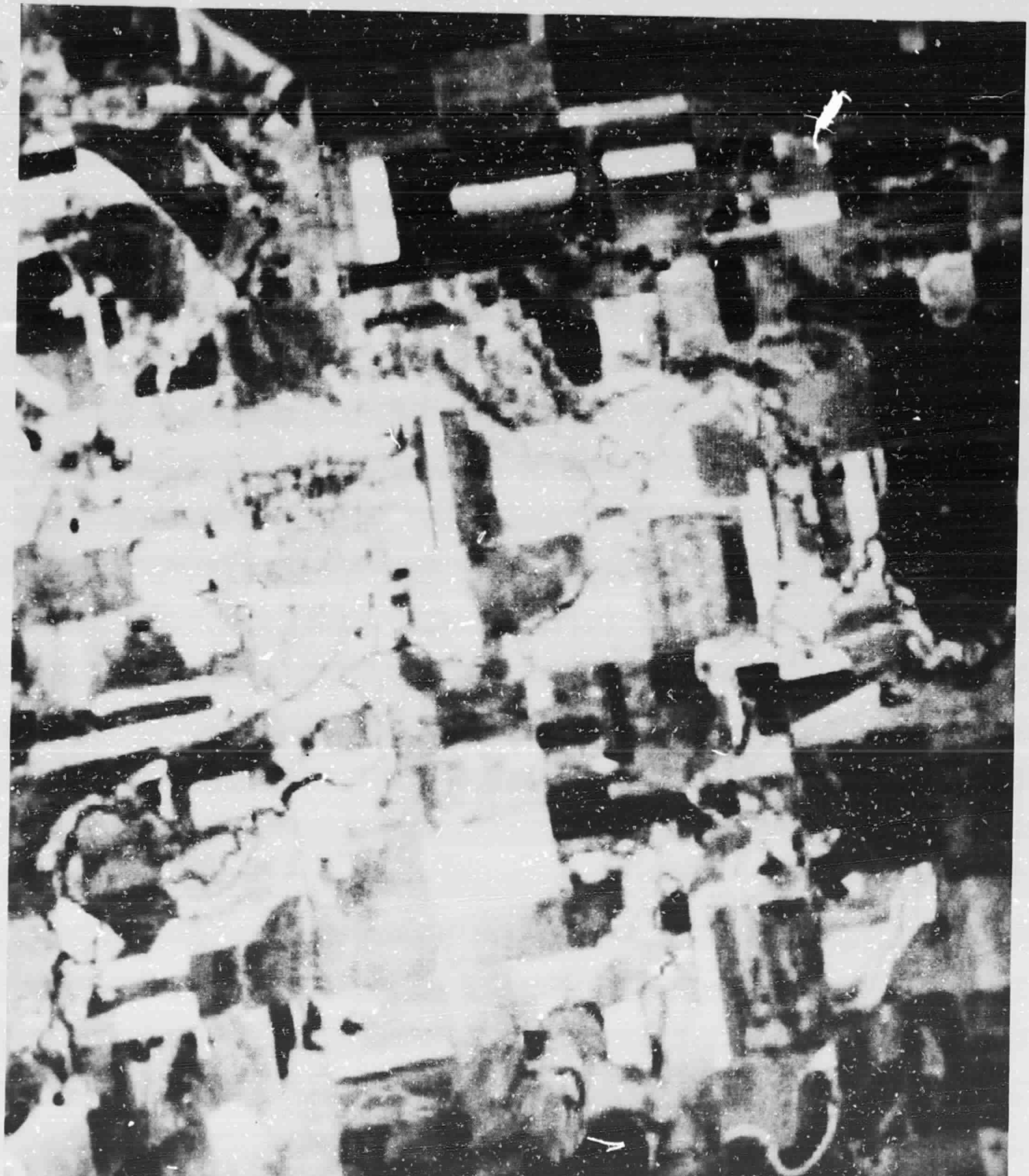

Figure 5

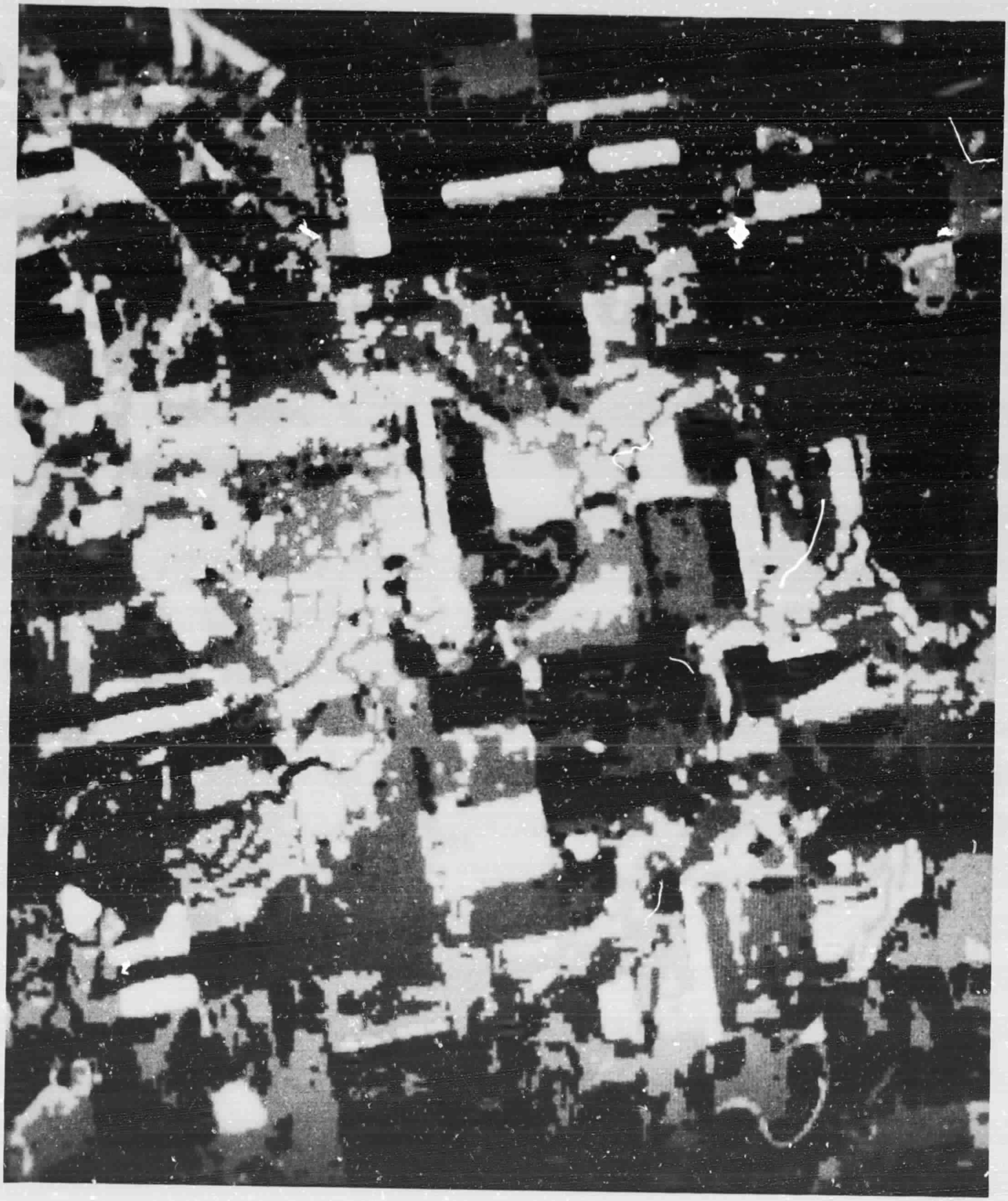

Figure 6

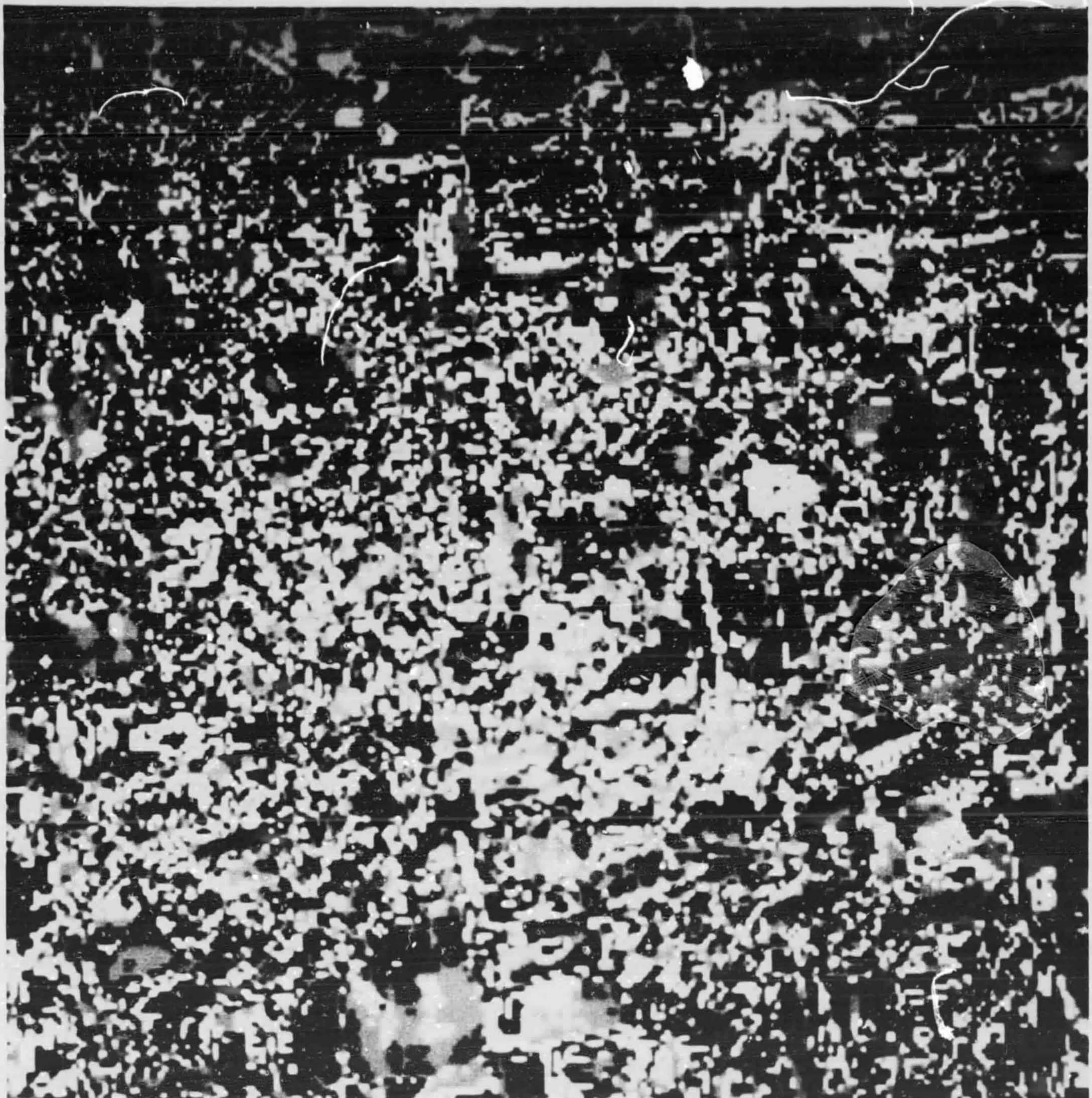

Figure 7

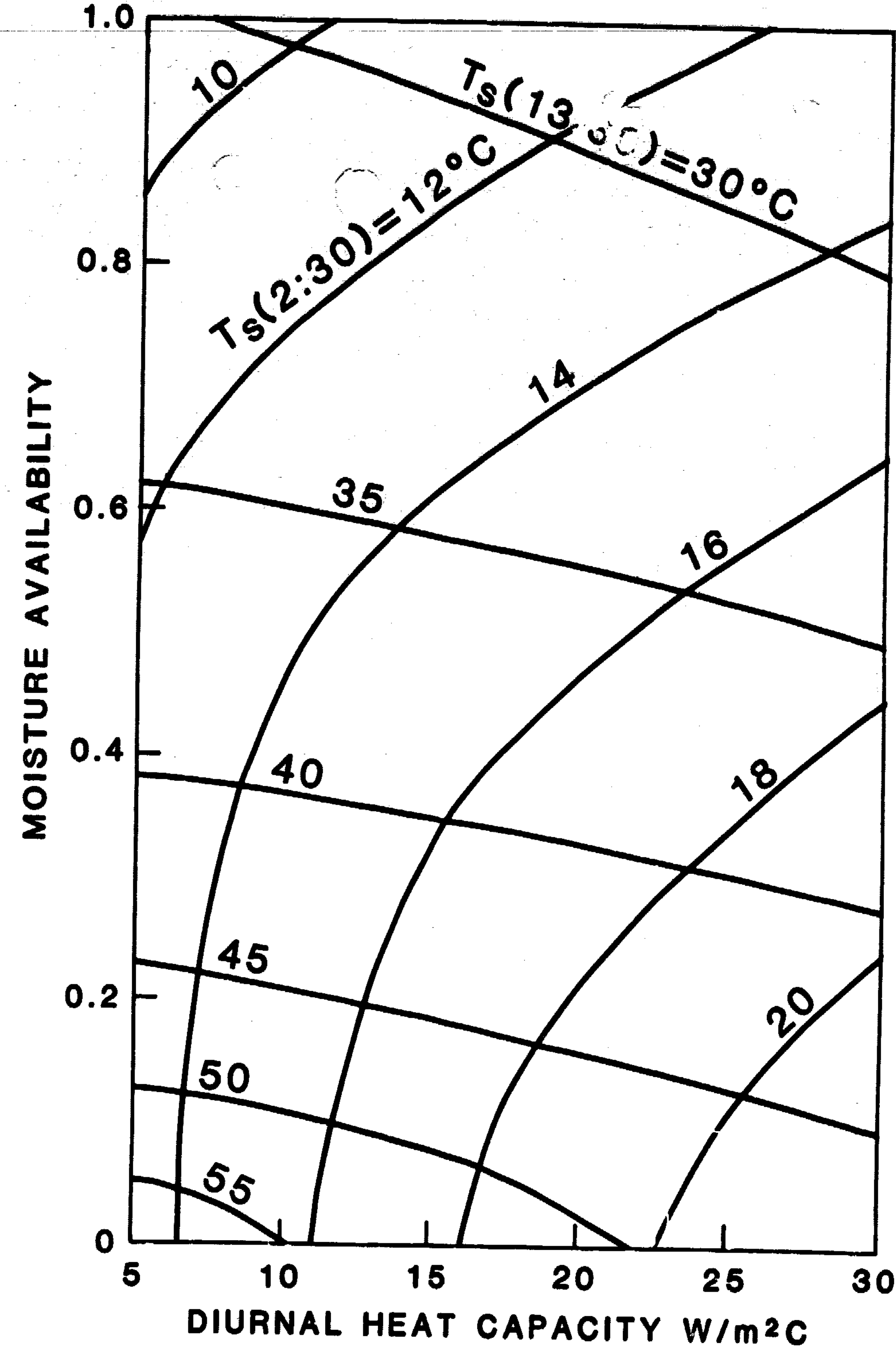
1.0
0.8
0.6
0.4
0.2
0
MOISTURE AVAILABILITY
5
10
15
20
25
30
DIURNAL HEAT CAPACITY W/m²C
10
Ts(2:30)=12°C
Ts(13:30)=30°C
14
16
18
20
35
40
45
50
55

Figure 8

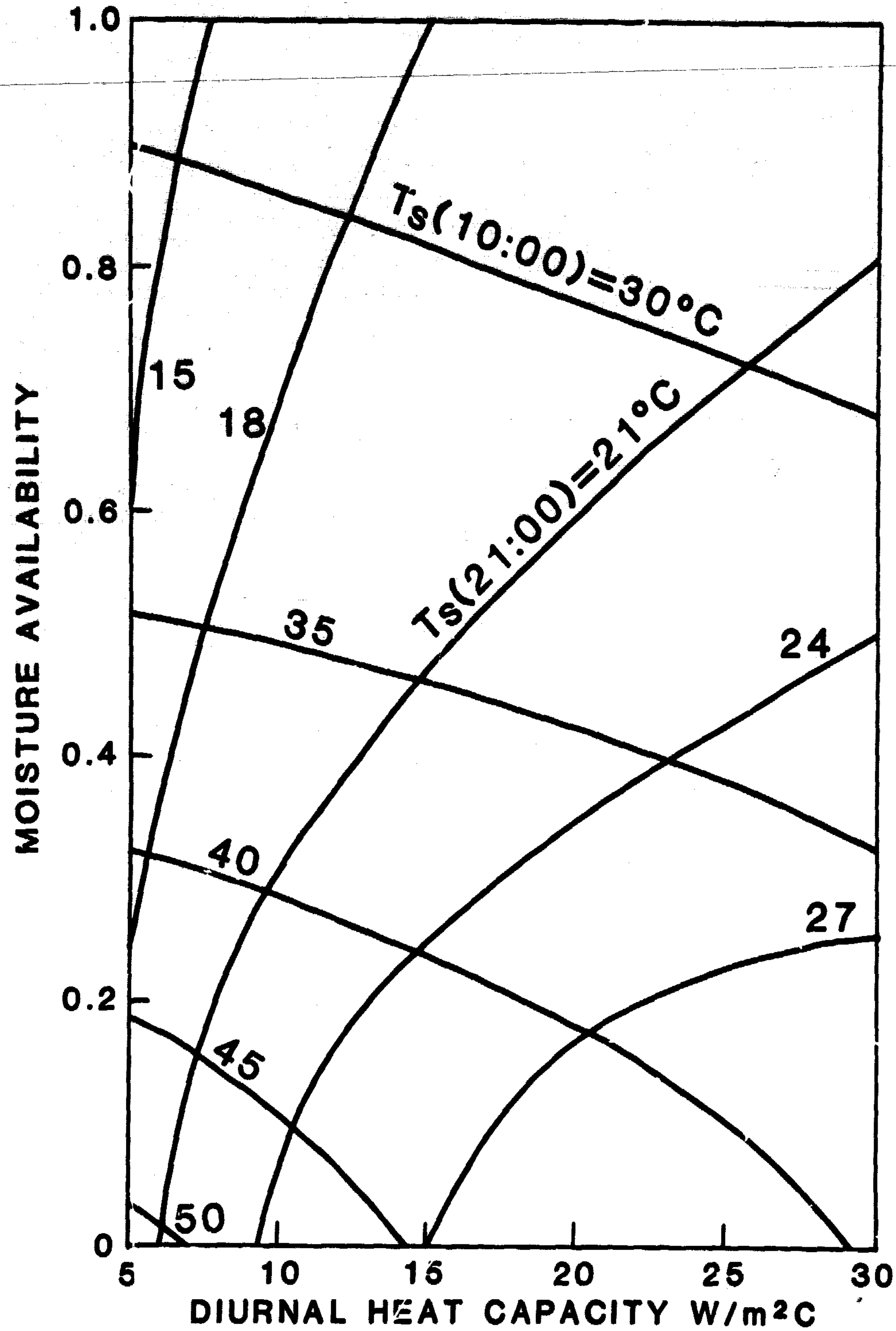
1.0
0.8
0.6
0.4
0.2
0
MOISTURE AVAILABILITY
5
10
15
20
25
30
DIURNAL HEAT CAPACITY W/m²C
Ts(10:00)=30°C
Ts(21:00)=21°C
15
18
35
24
40
27
45
50

Figure 9

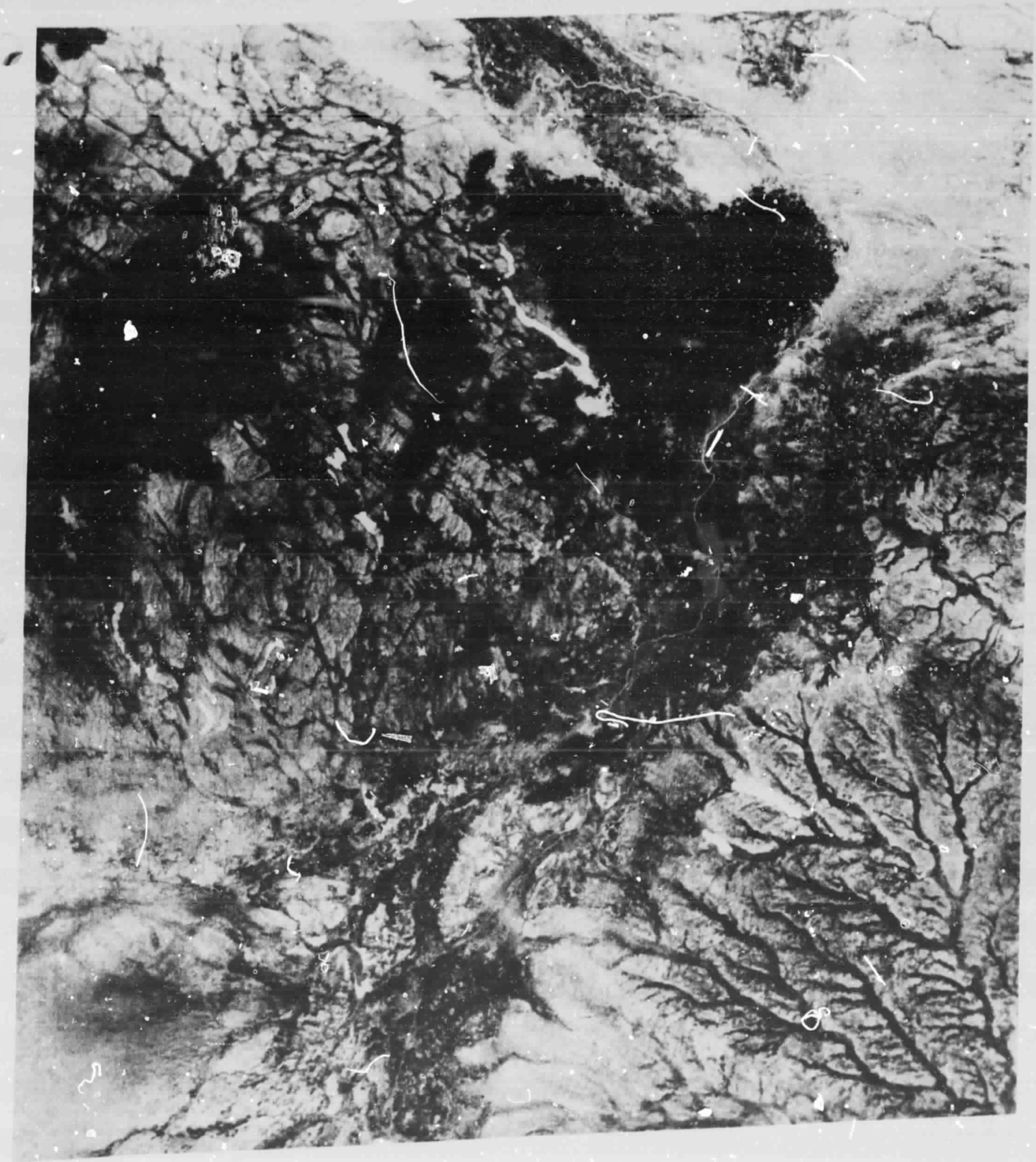

Figure 10

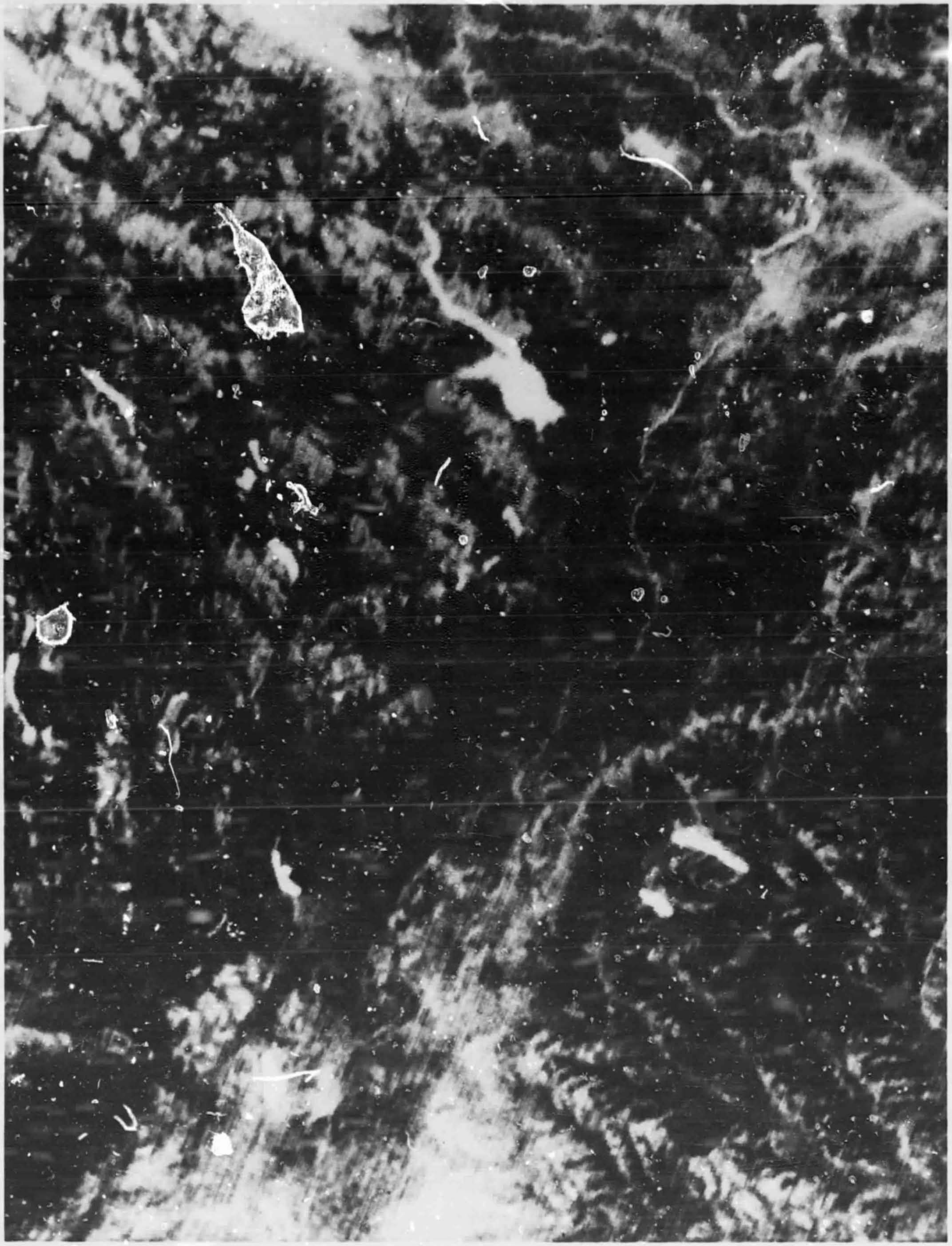

Figure 11

SECTION III. ADDITIONAL TECHNICAL INFORMATION

The following relates to the principal findings as given in the previous section.

A. The digital data studied were P tapes for both TM and MSS for the Iowa, Salton Sea, and Kentucky day scenes, and for the Adirondacks and Buffalo night TM scenes. The Arkansas scene was studied with P data for TM and A data for MSS. Both Arkansas and Iowa MSS data were processed at GSFC before the implementation of band decompression for band 4. Accordingly, the information content of the MSS band 4 data has been arbitrarily increased by one bit, which is consistent with results comparing bands 4 of TM and MSS for the other 3 daytime scenes.

B. Because of earth rotation and different pixel size the comparisons of MSS-A and TM-P represent slightly different areas for the Arkansas scene. This inconsistency has no significant effect on the comparison. By mistake the information content of a number of subscenes was initially evaluated for slightly offset areas (TM versus MSS). Evidently information content in bits per pixel varies slowly in space, since these offsets did not affect numerical values materially, i.e., of the order of tenths of a bit.

C. The tables for 15 subareas are given here as tables 6, 7, and 8. Tables 2, 3, and 5 of the previous section are averages of the 3 subareas from each scene.

Table 6. Information (bits/pixel) of multispectral data.

	Arkansas	Iowa	Kentucky	D. C.	California
Area 1			Thematic Mapper		
Band					
1	4.42	3.89	5.15	4.26	4.23
2	5.61	3.21	4.60	3.77	3.55
3	6.76	4.37	5.38	4.48	4.58
4	4.74	5.48	5.66	5.52	5.91
5	4.06	5.39	6.50	5.60	5.03
L6	5.19	4.83	6.07	4.87	4.77
SUM	30.78	27.17	33.36	28.50	28.07
			Multispectral Scanner		
1	3.42	2.94	4.22	3.39	3.24
2	4.12	3.80	4.85	3.93	4.12
3	5.35	4.72	5.12	4.79	5.27
4	5.77	4.66	4.81	4.58	5.19
SUM	18.66	16.12	19.00	16.69	17.82
Area 2			Thematic Mapper		
Band					
1	4.01	3.66	4.94	4.69	4.24
2	5.13	3.00	4.43	4.14	3.77
3	6.41	4.13	5.17	4.73	4.58
4	4.05	5.12	5.59	4.66	4.52
5	3.67	5.06	6.44	6.11	5.00
L6	4.48	4.59	5.79	5.30	4.71
SUM	27.75	25.56	32.36	29.63	26.82
			Multispectral Scanner		
1	3.19	2.80	4.02	3.86	3.34
2	3.59	3.56	4.64	4.32	4.02
3	4.90	4.39	4.98	4.33	4.01
4	4.48	3.35	4.72	3.74	3.88
SUM	16.16	14.10	18.36	16.25	15.25
Area 3			Thematic Mapper		
Band					
1	4.71	3.57	4.60	4.04	4.38
2	4.36	3.17	4.07	3.53	3.79
3	4.90	4.18	4.80	4.05	4.76
4	6.48	5.30	5.72	5.56	5.02
5	6.29	5.42	6.24	5.77	5.18
L6	5.47	4.72	5.53	4.77	4.64
SUM	32.21	26.36	30.96	27.72	27.77
			Multispectral Scanner		
1	3.91	2.73	3.93	3.24	3.40
2	4.38	3.63	4.65	3.52	4.21
3	5.30	4.44	4.99	4.88	4.43
4	4.62	3.40	4.80	4.66	4.28
SUM	18.21	14.20	18.37	16.30	16.32

Table 7. Information following principal components transformation.

	Arkansas	Iowa	Kentucky	D. C.	California
Area 1			Thematic Mapper		
Band					
1	6.81	5.88	6.97	5.98	5.90
2	6.07	5.32	5.61	5.42	5.33
3	4.41	4.23	4.59	4.50	4.09
4	3.38	3.23	3.71	3.24	3.01
5	2.71	2.92	2.91	2.75	2.47
L6	2.31	1.96	2.06	1.98	2.03
SUM	25.69	23.54	25.85	23.87	22.83
			Multispectral Scanner		
1	5.78	4.89	5.62	5.70	5.18
2	4.24	3.78	4.84	3.93	4.14
3	2.40	2.47	2.64	2.70	2.65
4	2.20	2.09	2.40	2.37	2.39
SUM	14.62	13.23	15.50	14.70	14.36
Area 2			Thematic Mapper		
Band					
1	6.42	5.54	6.83	6.41	5.63
2	5.52	4.89	5.57	4.54	4.68
3	3.86	3.94	4.46	4.26	3.99
4	3.20	3.07	3.34	3.14	2.86
5	2.56	2.77	2.77	2.75	2.47
L6	2.17	1.94	2.08	2.04	1.94
SUM	23.73	22.15	25.05	23.14	21.57
			Multispectral Scanner		
1	5.44	4.53	5.46	4.91	4.28
2	3.83	3.65	4.83	3.70	4.23
3	2.51	2.54	2.67	2.61	2.57
4	2.21	2.03	2.36	2.30	2.38
SUM	13.99	12.75	15.32	13.52	13.46
Area 3			Thematic Mapper		
Band					
1	6.56	5.72	6.59	6.11	5.66
2	6.51	5.28	5.73	5.39	5.27
3	4.83	3.28	4.27	4.00	4.44
4	3.54	3.02	3.26	2.93	2.92
5	2.91	2.90	2.74	2.82	2.62
L6	2.34	1.98	2.02	1.98	1.93
SUM	26.69	22.18	24.61	23.23	22.84
			Multispectral Scanner		
1	5.69	4.60	5.45	5.27	4.76
2	4.65	3.70	4.91	3.69	4.33
3	2.52	2.41	2.64	2.70	2.61
4	2.27	1.98	2.37	2.32	2.40
SUM	15.13	12.69	15.37	13.98	14.10

Table 8. Information following delta (difference) transformation.

		Arkansas	Iowa	Kentucky	D. C.	California
Area 1				Thematic Mapper		
	Band					
	1	5.05	4.38	5.33	3.57	4.94
	2	4.69	4.14	4.47	3.56	4.38
	3	3.69	3.35	4.06	3.08	3.98
	4	3.10	2.89	3.35	2.89	3.22
	5	2.71	2.84	2.87	2.47	2.75
	L6	2.20	1.96	2.06	2.02	1.98
	SUM	21.44	19.56	22.27	17.59	21.25
				Multispectral Scanner		
	1	4.50	4.05	4.56	4.42	3.87
	2	3.60	3.23	3.90	3.64	3.07
	3	2.40	2.47	2.64	2.67	2.70
	4	2.20	2.09	2.40	2.39	2.37
	SUM	12.70	11.84	13.50	13.32	12.01
Area 2				Thematic Mapper		
	Band					
	1	5.29	4.00	5.23	4.87	4.33
	2	4.49	3.59	4.51	3.73	3.44
	3	3.63	3.08	3.97	3.54	3.49
	4	3.17	2.77	3.22	2.94	2.84
	5	2.56	2.73	2.77	2.75	2.47
	L6	2.17	1.94	2.08	2.04	1.94
	SUM	21.21	18.11	21.78	19.87	18.51
				Multispectral Scanner		
	1	4.50	3.63	4.52	3.91	3.54
	2	3.32	3.04	3.81	3.16	3.43
	3	2.51	2.54	2.67	2.61	2.57
	4	2.21	2.03	2.36	2.30	2.38
	SUM	12.54	11.24	13.36	11.98	11.92
Area 3				Thematic Mapper		
	Band					
	1	5.35	4.28	5.08	4.83	4.15
	2	5.19	3.93	4.60	4.15	3.86
	3	4.16	3.13	3.87	3.60	3.56
	4	3.40	2.80	3.17	2.93	2.84
	5	2.89	2.86	2.74	2.72	2.62
	L6	2.30	1.98	2.02	1.98	1.93
	SUM	23.20	18.98	21.48	20.21	18.96
				Multispectral Scanner		
	1	4.36	3.73	4.52	4.29	3.77
	2	3.95	3.12	3.90	3.14	3.42
	3	2.52	2.41	2.64	2.70	2.61
	4	2.27	1.98	2.37	2.32	2.40
	SUM	13.10	11.24	13.43	12.45	12.20

D. System noise figures appear to be very low for TM, while the 'woodgrain noise' is objectionable for MSS. Estimates were not developed because other investigators and the Landsat project had already reported results long before evaluation was feasible under this investigation.

E. The comparison of TM imagery with HCMM imagery as illustrated in Section II is believed to be representative. However, conclusions regarding TM thermal IR data are somewhat conjectural due to the very limited availability of night data. The following figures (12-15) show that considerable variability may be expected in night IR data, depending principally on the occurence of low lying fog and/or haze. The TM scenes probably represent optimum viewing conditions, given the considerable spatial detail which is evident in the data. Contrast enhancement simply exaggerates the noise and band to band striping in the TM data. The TM night data has, in effect, a very low signal to noise ratio.

Figure 12. Night thermal infrared image as acquired by HCMM over the same area shown in figures 10 and 11. Haze obscures many features and reduces contrast. Scene number A0041-07360.

Figure 13. Landsat band L7 image over Buffalo, New York. Scene number E-40037-02243.

Figure 14. HCMM night IR image corresponding to figure 13. Note that the contrast range of land features is considerably greater than in the previous (TM) scene. Scene number A0041-07360.

Figure 15. HCMM night image for the same area as figures 14 and 15. Haze obscures many features. Scene number A0078-07250.

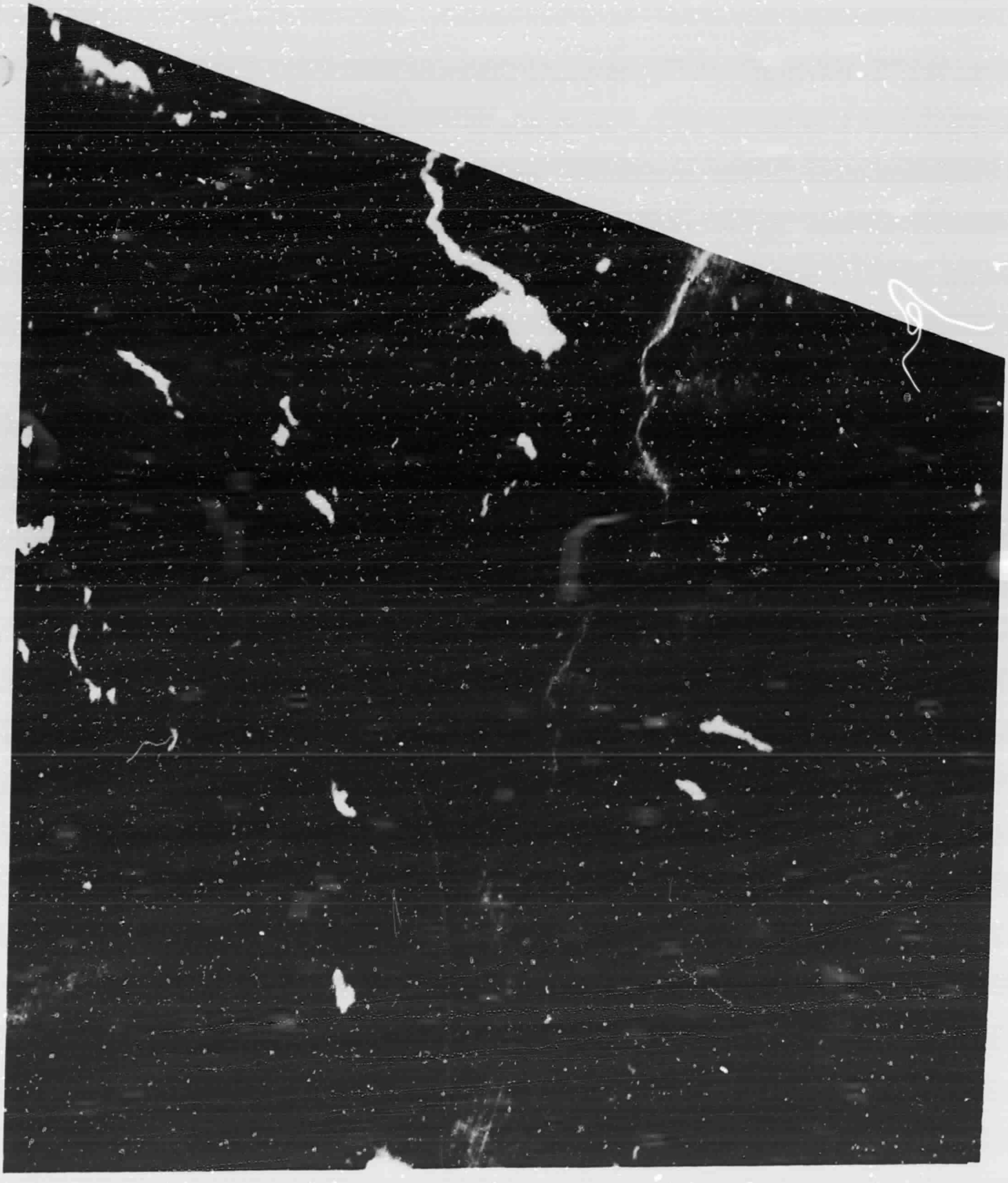

Figure 12

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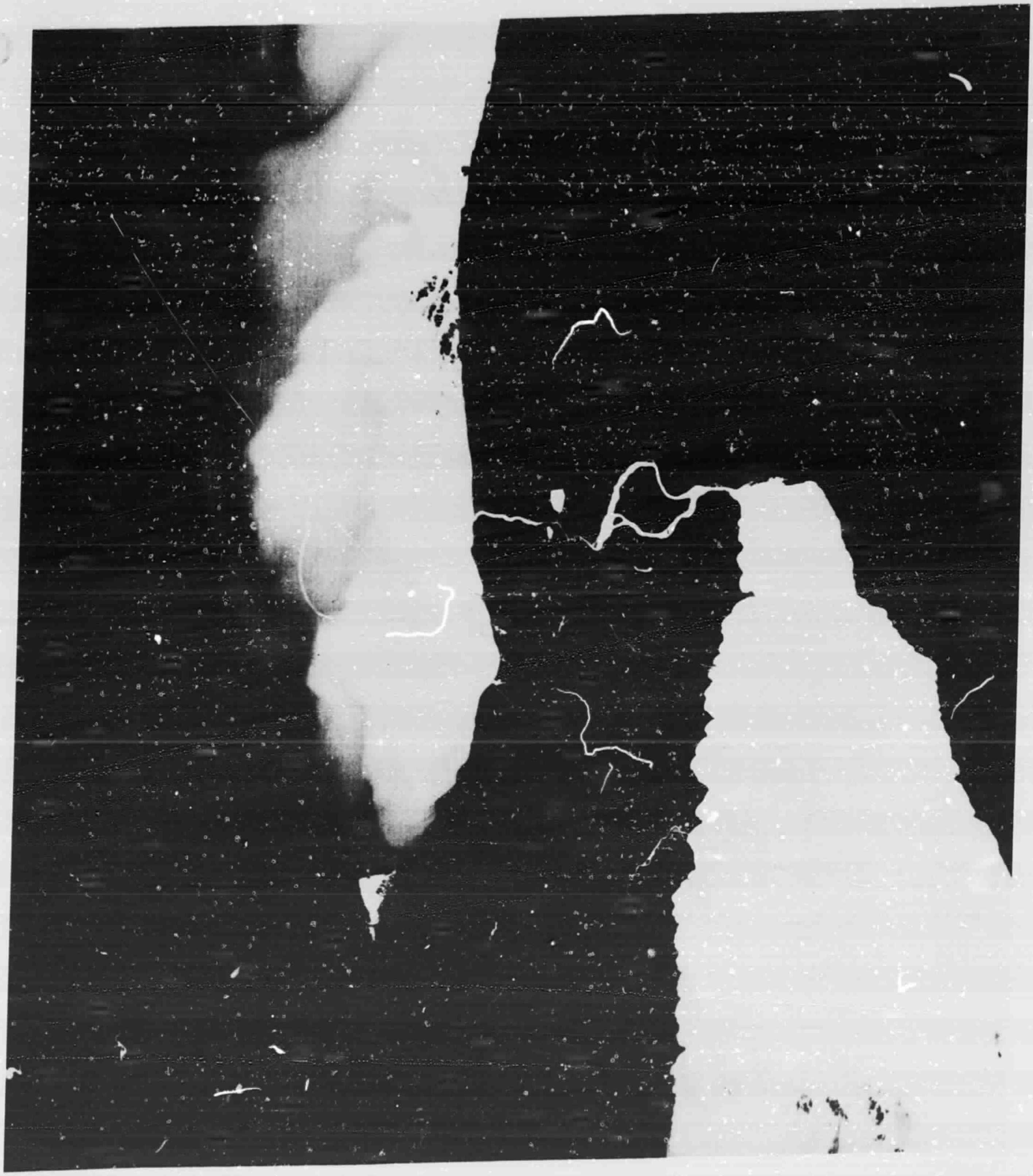

Figure 13

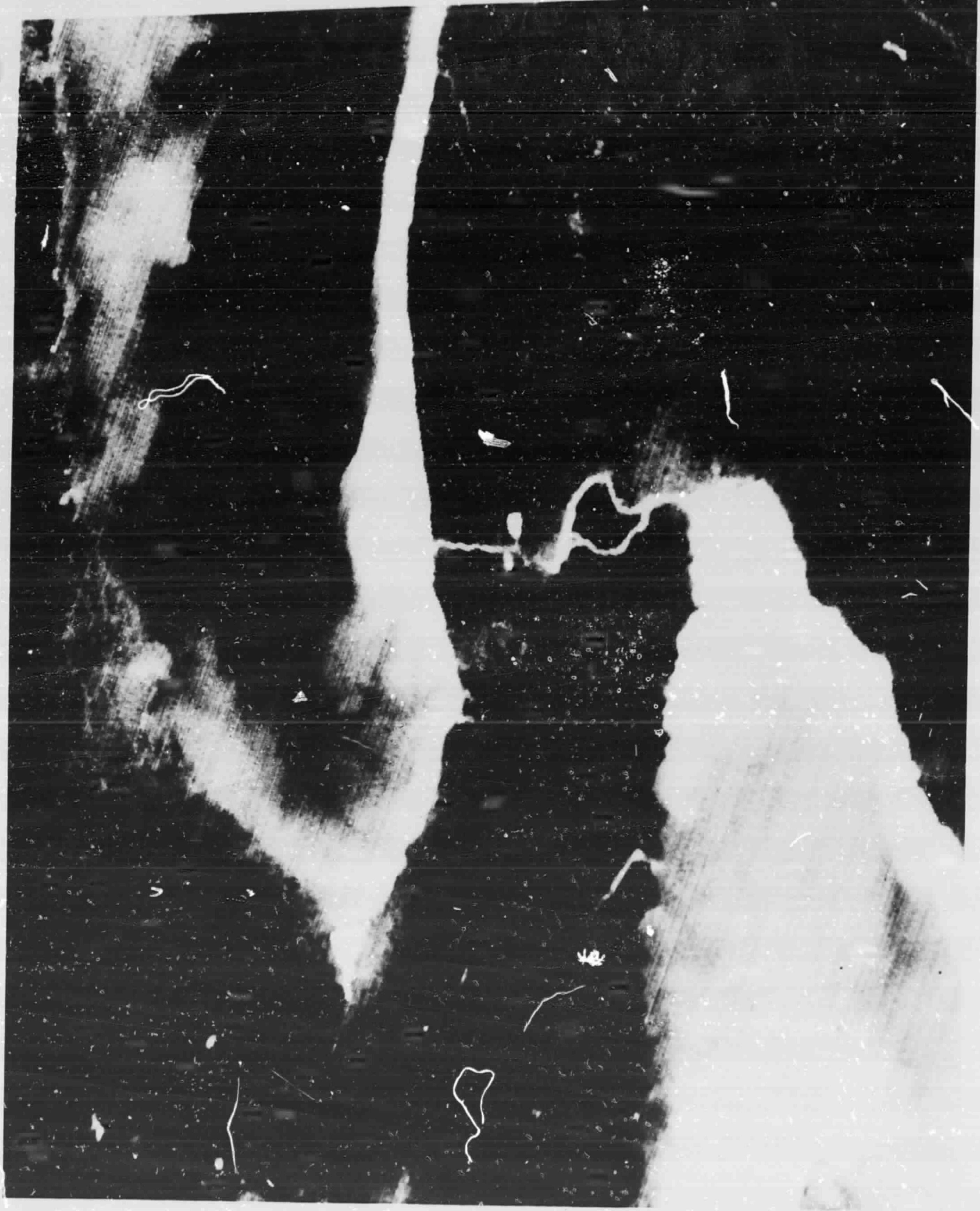

Figure 14

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Figure 15

SECTION IV. RECOMMENDATIONS

A. As discussed in Section II the thermal IR data (Channel L7) of the TM have low utility because of the uncertainty in interpretation of a single temperature measurement during the 24 hour diurnal cycle, and because the 16 day repeat cycle of data acquisition is too long for monitoring environmental factors such as moisture conditions. However, advances in remote sensing technology[1] suggest a plausible extension of the Thematic Mapper thermal IR observations. This would require a multispectral thermal IR sensor in the Landsat 4 (or 5) orbit, but preceding Landsat in the early morning just before sunrise, for example at 4 a.m. local time. Data from this satellite could be combined with that from the L7 data of the TM to produce yield information on moisture conditions, on soil types, and on thermal patterns associated with geologic variations of rocks and minerals.

B. The efficiency of an observing instrument in acquiring information, as expressed by the ratio (bits per pixel in real data)/(possible bits per pixel)*100, is very much a function of instrument design. It is recommended that this factor be computed explicitly from simulation data, such as from aircraft, during consideration of design alternatives for future observing systems. The limited value of MSS channel 3 is widely known, for example. It results from the redundancy between MSS channels 3 and 4.

C. The advent of inexpensive microprocessors makes user-transparent data compression techniques a cost effective possibility in satellite systems, and in user data processing systems. These possibilities should be explored, both by system engineers and by applications scientists.

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[1]Kahle, A. B. and Goetz, A. F. H., 1983, Mineralogic information from a new airborne thermal infrared multispectral scanner, Science 222, pp. 24-27.

SECTION V. PROJECT FUNDING

Funding was billed at per quarter for the first three quarters, with the balance of approximately billed in the 4th quarter. Funding went largely to computer time, support of drafting, photo services, etc., and to general support.

INFORMATION CONTENT OF DATA FROM THE LANDSAT-4 THEMATIC MAPPER (TM) AND MULTISPECTRAL SCANNER (MSS)

US Department of Agriculture, Agricultural Research Service

STATEMENT OF WORK: A-15

This statement of work consists of the objective to be addressed by the investigation, the tasks required to satisfy those objectives, and the approach to accomplishing each task.

Objective

The objective of the proposed work is to quantify the increased information content of TM data compared to that from the Landsat-4 MSS.

Tasks

The following tasks are to be performed on TM and MSS data sets:

a. Characterize instrument performance in terms of noise, band-to-band registration and calibration, data processing algorithms, etc.

. Apply a principal components transformation to reflectance data to facilitate reduction of the number of spectral channels in task d.

c. Perform supervised classification to identify surface types or "themes."

d. Compute within-class means and standard deviations and obtain a corresponding classification significance score for each spectral eigenvector.

e. Compute the spectral information content of TM and MSS data as a function of the number of spectral bands and the between-class/within-class signal to noise ratio.

f. Estimate the spatial information content of the two data tapes.

g. Estimate the significance and information content of thermal IR data from TM as a separate data type.

h. Estimate the net information content of the TM and MSS (bits/hectare) for the scenes selected.

i. Submit quarterly progress reports, the first being due 3 months after the initiation date of the contract. A draft final report for NASA's review and comment and a final report based upon that review are due 2 months prior to and at the close of the contract period, respectively.

Approach

This analysis will involve the application of standard mathematical methods (principal components, supervised classification, autocorrelation, etc.) to data sets from the MSS and TM. Functioning information theory software will be adapted to the proposed tasks. Ultimately, the amount of unique information contained within a TM/MSS (sub) scene will be estimated by eliminating spectral and spatial redundancy from both data types. Eigenvectors will provide the basis for truncation of the expansion of spectral data into spectral components; analysis methods such as Fourier transforms and autocorrelation will be used to estimate the spatial information content.

Imperfections in instrument performance characteristics may be treated as equivalent to noise sources which correspond to "information" as defined by this investigation. Documentation and where possible elimination of this type "information" will be accomplished through a study in concert with results obtained by the Science Office of the relationship between instrumentation, data processing, and ground characteristics.